Journal of Energy Storage 42 (2021) 103011

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Techno-economic analysis of control strategies for heat pumps integrated into solar district heating systems

Mohamed Hany Abokersh [a], Manel Vallès [a], Kangkana Saikia [a], Luisa F. Cabeza [b], Dieter Boer [a,*]

[a] *Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, Tarragona, Spain*
[b] *GREiA Research Group, INSPIRES Research Centre, Universitat de Lleida, Lleida, Spain*

ARTICLE INFO

Keywords:
Seasonal energy storage
Solar district heating
Heat Pump control
Energy Efficiency
Life Cycle Costing

ABSTRACT

This present work focuses on assessing the techno-economic benefits of different control strategies for a heat pump integrated into the solar assisted district heating system (SDHS). The system has been developed using dynamic simulation software (TRNSYS) and optimized based on a genetic algorithm. With an industrial-sized heat pump connected to thermal storage tanks for domestic hot water (DHW) and space heating (SH) for the requirements of the community, a SDHS is operated by applying two different control mechanisms for the heat pump based on its reference operating temperature. The application of the methodology is applied to a residential neighborhood community of 10 buildings located in Madrid to act as a proxy for the Mediterranean climates. The results showed a significant effect for the heat pump control in the techno-economic benefits where the proposed system is able to provide a solar fraction up to 99%. Furthermore, the total electricity consumption of the heating system varied by 10% between the best and the worst cases. Besides, the annual seasonal storage efficiency improved up to 90% with a life cycle expense up to 67.12 Euro/MWh, and a payback period of 29 years.

1. Introduction

Energy infrastructure around the world is undergoing a transitional period to accommodate the highest possible share of renewable energy generation in the existing grid and provide reliable service to meet the demand in various sectors. With the revised EU directive on renewable energy, the European countries are focusing on providing 32% of the total energy from renewable energy sources, such as wind, solar and biomass [1]. In efforts to push this energy transition, the EU has also decided that, starting from 2021, the share of renewables in the heating and cooling sector will rise by 1.3% annually [2]. In this context, district heating networks have gained a great deal of attention with the possibility of integrating them into the future smart energy system.

The smart energy system concept is a wider definition of the smart grid moving the sole focus from electrical power grids towards the integration of different energy sectors such as electricity, heating, cooling, industry, buildings, and transportation to achieve sustainable energy solutions [3]. In such a future smart energy scenario, the district heating systems can play a key role by allowing the use of industrial waste heat and solar energy in combination with large-scale thermal energy storage to transition towards low-temperature thermal grids [4–6].

Most of these district heating networks are in Germany [7], Denmark, and Sweden [8]. In some solar communities, thermal energy storage is used. In recent studies, water-based storage tanks are also being considered [9]. Currently, Denmark is trying to design large solar district heating systems (SDHS) that depend on the water pit storage [10]. In Germany, the Neckarsulm community was developed in 1997 that comprises of a gym, school, shopping center and 200 housing apartments. A BTES (borehole thermal energy storage) of 63,000 m^3 capacity is installed [11] and a heat pump along with the gas boiler was set up for the backup. Similarly, the Crailsheim community was developed based on a 37,500 m^3 BTES in 2007. This community contains a gym, school, and 260 housing apartments [12]. This community was backed up by the district heat pump. The storage capacity of the Crailsheim is lesser than Neckarsulm but the solar collectors installed in Crailsheim (7500 m^2) are comparatively larger than Neckarsulm (5670 m^2). There are small solar communities as such as the Attenkirchen solar community that only consists of 30 homes [13]. An underground water tank that is surrounded by 10,500 m^3 BTES is used in this community. The same design was copied for the sole Finnish solar community that was developed in Kerava [14]. However, the community was dismantled and converted back to the SDHS. Drake Landing Solar Community in

* Corresponding author.
E-mail address: dieter.boer@urv.cat (D. Boer).

https://doi.org/10.1016/j.est.2021.103011
Received 11 September 2020; Received in revised form 10 June 2021; Accepted 24 July 2021
Available online 5 August 2021

Nomenclature

A_{COL}	total aperture area of solar collectors (m^2/(MWh·a))
β_{COL}	inclination angle of the solar collectors (^{o})
CAP_k	design variable of equipment unit k
$CEPCI^{year\ A}$	chemical engineering plant cost index in the base year
$CEPCI^{year\ B}$	chemical engineering plant cost index in the installation year
Con_{SST}	purchase cost of the construction material of the seasonal storage tank (€)
C_{AUX}	initial investment cost (€)
FC_{AUX}	contribution of the auxiliary heater as a percentage of the maximum heating load (-)
$f_c(x)$	original objective function [$LCOH$(x)]
FC_{HP}	fraction capacity of the heat pump as a percentage of the maximum heating load (-)
FBM_k	bare module factor of equipment unit k
i	annual inflation rate (%)
$g(x)$	inequality constraints
$h(x)$	equality constraints
HDR	seasonal storage tank aspect ratio (m/m)
HDR_{DHWT}	domestic hot water storage aspect ratio (m/m)
LCC	levelized cost of heat (€/MWh)
N_{COL}	number of solar collectors in series
PEC_k	purchase cost of equipment unit k (€)
PWF_n	present worth factor of periodic future cash flow (-)
PVF_n	present value factor of single future cash flow at the beginning of nth time period (-)
$\dot{Q}_{DHW\ loss}$	heat loss rate through the domestic hot water storage tank (MW)
$\dot{Q}_{HE}$	heat transfer rate through the heat exchanger (MW)
$\dot{Q}_{AUX}$	duty of auxiliary heater (MW)
$\dot{Q}_{consumption}$	electricity consumed by heat pump (MW)
$Q_{Heating\ load}$	total space heating demand (MWh)
$Q_{DHW\ load}$	total domestic hot water demand (MWh)
$Q_{SST\ loss}$	total energy losses through the seasonal storage tank (MWh)
SF_{DHW}	annual solar fraction for the DHW distribution circuit (%)
SF_{SH}	annual solar fraction for the SH distribution circuit (%)
T_{Col}	exit temperature at the solar collector (°C)
T_{ref}	turn on temperature of the heat pump (°C)
T_{SST}	mean temperatures of the seasonal storage tank (°C)
T_{DWHT}	mean temperatures of the domestic storage tank (°C)
V_{DHWT}	volume of the domestic hot water tank (m^3/(MWh·a))
V_{SST}	volume of the seasonal storage tank (m^3/(MWh·a))
η_{SST}	efficiency of the seasonal storage tank
COL	solar collector field
COP	coefficient of performance
CEPCI	chemical Engineering Plant Cost Index
DHW	domestic Hot Water
DHWT	domestic Hot Water Tank
HE	heat Exchanger
HP	heat Pump
HPC	high-Performance Concrete
NPC	net present cost
MOO	multi-Objective Optimization
MOGA	multi-Objective Genetic Algorithm
MW	mineral Wool
P	mentrifugal pump
PB	payback Period
SDHS	solar Assisted District Heating System
SH	space Heating
SST	seasonal Storage Tank
STES	seasonal Thermal Energy Storage
TES	thermal Energy Storage
TRNSYS	transient system simulation program

Canada is the well-known solar community which became functional in 2008 [15]. It consists of 2300 m^2 solar collectors and two 34,000 m^3 BTES systems. It supplies heat to 52 houses. The Drake Landing community meets 98% of the total demand for space heating.

Such the SDHS have an edge over the conventional heating system (Natural gas boiler) in terms of energy savings and emissions [16]. However, it deals with a higher degree of flexibility issues due to the fluctuating nature of solar radiation potential for energy generation and high heat losses from the thermal storage [17]. Owing to large heat utilization in the building, a large return temperature to the storage, and a high thermal waste, the heating systems struggle to achieve a solar fraction of 50-100% for seasonal storage and 10-20% for everyday storage [18]. In Friedrichshafen, Germany, the performance of the solar fraction is estimated to reach up to 43%. Nevertheless, under realistic operation setup, the monitoring data indicated that a solar fraction between 21% and 33% is attainable [11]. Higher solar fraction value has never been obtained as a result of many problems such as higher heating demand in comparison to expectation, increased thermal losses in the seasonal storage, and reduced heat exchanger and solar collector efficiencies [19]. Similar problem has been detected in other SDHS installed in Rockstock and Neckarsulm [20]. Besides, the installed plants in Hamburg, Steinfurt-Borghorst, and Neckarsulm II show a significant deviation between the monitored performance and design as a result of the high thermal losses in the seasonal as well as other tanks, smaller solar collector area than the planned, and high net return temperature [21]. The SDHS built-in Crailsheim-Hirtenwiesen was meant to cover 50% of the heating needs of a residential area that has 260 apartments, a gym, and a school. To make sure that the system is accessible all year, a borehole that can store up to 10000 m^3 per season was added to the system [22]. When the performance was monitored, there was a considerable difference between the real and estimated solar fraction by up to 60%. This huge difference is as a result of the ground losses in addition to higher operating temperature in the space heating network [23]. The Drake Landing Solar Community in Canada is the most well-known solar community. This system has been able to use solar energy to cover 98% of the space heating demand [15]. However, during five years of monitoring, a high-performance variation was noticed in this solar community. A report from ASHRAE [24] stated that the reason for the system's underperformance in comparison to the simulation results is the high thermal losses all over the network, pump control, and the stratification of the storage tank. Apart from the abovementioned issues, Weissmann et al.[25] stated that the orientation of the building, the orientation of the thermal collector in addition to the pipe leakages could have an adverse effect on the performance of the SDHS. Moreover, the high investment cost of seasonal thermal energy storage (STES) is usually a major drawback. Also, issues with the availability of space, the presence of groundwater tables, and complex planning layout are the main challenges that should be dealt with in STES, among others [26]. To increase the advantages of a STES, the optimal size and design of STES as well as the appropriate components (e.g. discharging/charging devices) should be well planned as mentioned by Abokersh et al.,[27, 28].

One way to reduce the storage heat loss is to maintain a low temperature inside the storage tank. Such control measures require a supporting device such as heat pumps to make up for effective space heating [29]. On the other hand, introducing a heat pump in a low-temperature

SDHS with seasonal storage can be a promising solution to improve the overall system efficiency as heat pumps are more efficient to supply low temperature [30]. Furthermore, by producing a low-temperature profile, a higher solar contribution can be achieved [31].

There are many instances where the role of heat pump has been investigated in a solar assisted district heating with seasonal storage. Various simulation and optimization studies have been conducted to estimate the performance of solar assisted heat pumps. The study from Bellos and Tzivanidis applied a multi-objective procedure with heating and electricity production as the objective functions in a solar heating-electricity production using Photovoltaic thermal hybrid solar collector and a heat pump for building applications [32]. Hirvonen et al. performed dynamic TRNSYS simulations and optimization on a solar district heating system with seasonal thermal energy storage under Finnish weather conditions considering different community sizes [26]. Another study optimized and compared a centralized solar district heating design with a semi-decentralized and found that the decentralized system outperforms the centralized system in terms of life cycle cost [33]. These studies highlight that heat pumps can add more flexibility by shifting the use of electricity to supply the space heating load improving energy security from a smart grid point of view. Also, it can help to implement demand-side management strategies while integrating renewables on the building level. These add-on advantages, along with its proven technology, have put heat pumps in an exciting position at the cost of higher electricity consumption, CO_2 and investment cost [34]. All these analyses were primarily focused on parameters associated with the solar source, storage and demand profile of the community from the economy, and system efficiency point of views [9]. However, efforts towards designing an optimized district heating framework from the sustainability standpoint are seldom found [35]. The integration of heat pump into the SDHS with seasonal storage should be optimally configured considering the three main aspects, i.e. energy efficiency, economy and environmental impact simultaneously to ensure that such a system is walking hand in hand with the sustainable development goal.

Along with that, the crucial role of heat pumps to address the storage heat loss and overall temperature stability of the thermal network to facilitate low-temperature district heating has not been fully explored [36]. Therefore, the main novelty of this work is to demonstrate the sustainable potential of heat pump integration into a community-sized SDHS to stabilize its performance and trace its techno-economic failures. Such a system is investigated under two control strategy for the heat pump using a dynamic simulation (TRNSYS) in an optimization framework for all the associated parameters that can be generated considering the energy efficiency and life cycle cost. The current study may, therefore, act as a deciding tool which evaluates the capacity for heat pumps to be coupled with SDHS and thermal storage and subsequently, providing a complete picture to the stakeholders for the clean energy transition.

2. System methods evaluation

2.1. Energy system details and modeling

A distinct typology of heat pump integrated SDHS is designed to meet the space heating (SH) and domestic hot water (DHW) demand for a hypothetical residential community throughout the year as schematically shown in Fig. 1. The system mainly consists of solar collectors, a half-buried sensible seasonal storage tank (SST), the DHW storage tank (DHWT), a water-to-water heat pump unit and an auxiliary natural gas heater.

The heat pump (HP) acts as a heat source for the SST when connected in the solar field circuit, as shown in Fig. 1. In this configuration, the heat captured by the solar collector field (COL) can be directly used to fulfil the SH or DHW demand of the district or stored in the SST. The heat exchangers transfer the heat from the supply circuit to the distribution network using Y-type valves depending on the mode of operation. Under a certain condition, the heat produced by the HP is either distributed directly for SH or supplied to the SST for charging up the heat stored. The SST is used during the winter season to supply the SH demand while the short-term storage DHWT is used to supply the daily DHW demand. It is important to note here that the heat provided for SH corresponds to a low-temperature level (50°C), whereas the heat provided to the DHW

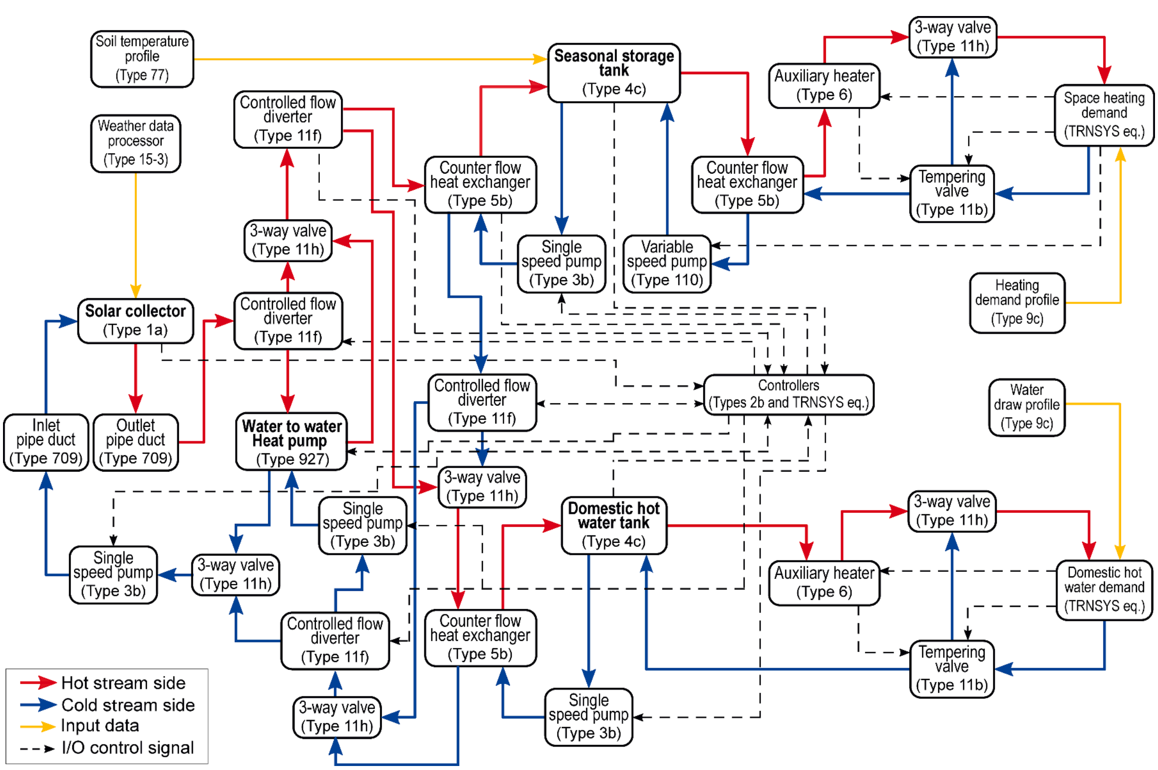

Fig. 1. A schematic drawing for the HP integrated with SDHS.

is at high-temperature level (60°C). Finally, if the solar field, SST and HP fail to meet the heat demand, the mismatch is covered by the auxiliary heater.

2.2. SDHS control strategies

An efficient control strategy is adopted to meet the residential neighbourhood heating demand maximizing the use of solar energy and minimizing the network heat losses. Four modes of operation are planned considering the temperature levels of SDHS, which are enabled via on-off control switches. At the start:

1. In the first operational Mode or DHW operation mode, the heat obtained by solar collectors is transported to the DHWT with the help of P1, P2, and P5 pumps through HE2. When the solar thermal energy is not enough to satisfy the demand in the DHW network, the auxiliary heater (AUX2) is enabled. During DHW mode, the HP unit does not operate.
2. In the second mode, the SH gets initiated when a suitable level of temperature in DHWT (T_{DHWT}) is reached while the temperature of the collector (T_{COL}) is at a higher temperature than the bottom of the SST (T_{SST}). In this mode of operation, P1, P2, P3 pumps are used to transfer heat to SST from ST via HE1.
3. In the third operation mode, a concurrent operation of DHW and SH circuits gets initiated when the criteria of DHW and SH operations are met and $T_{SST} > T_{DHWT}$.
4. Finally, the heat pump operation has two activated modes:

• ***Control (A)*:** In this mode, the heat pump works when the mean SST temperature (T_{SST}) is lower than a reference heat pump turn on temperature (T_{ref}).
• ***Control (B):*** In this mode, the heat pump works if the solar collector temperature (T_{COL}) is lower than the mean SST temperature (T_{SST}), which is, in turn, lower than a reference heat pump turn on temperature (T_{ref}).

In these modes of operation, the heat generated by the heat pump in control (A) & (B) will be transferred to either the SST or the DHWT based on demand. In case of insufficient supply from SST or DHWT, the auxiliary heater is turned on. A drawing schematic for the control strategies is shown in Fig. 2.

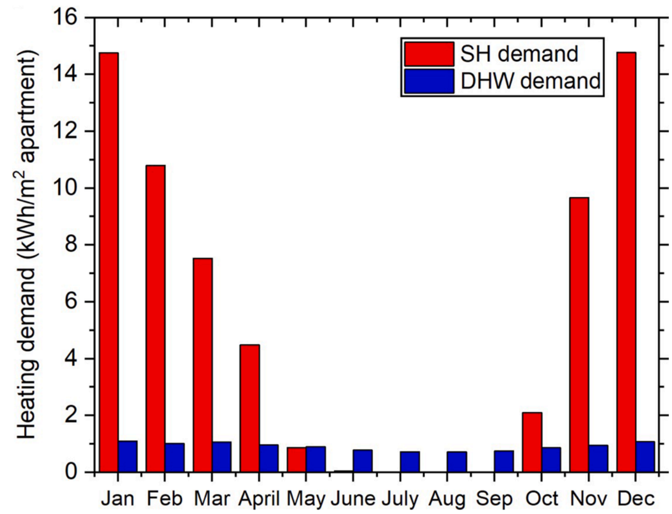

Fig. 3. Monthly SH and DHW demand for a neighborhood of 10 residential buildings located in Madrid.

2.3. TRNSYS simulation model

TRNSYS 18, transient simulation software, is employed to analyze the dynamic behavior of the proposed SDHS. The software operates by solving partial differential equations of the mass and energy balances within previously defined boundaries. The dynamic nature of the program intends to offer a realistic simulation of the SDHS plant. On the other hand, to reduce the computational cost, the model is simulated over a typical year of operation, and the solution is extrapolated over the plant lifetime assuming same climatic conditions and demand profiles year after year. The SDHS model validation is performed based on the implemented work by Abokersh et al. [35] and Tulus et al. [37], incorporating the hybrid solar circuits and their control schemes. The information flow diagram is shown in Fig. 1. (Type – inside TRNSYS GUI).

Each component has information boxes for component-specific parameters and input-output variables. Mainly the model includes the following types: flat plate solar collectors (Type 1a) with an optical efficiency of 0.817, heat loss coefficient of 2.205 W/m^2·K; water to the water heat pump (Type 927); fully stratified storage tanks (Type 4c) with heat loss coefficient of 0.3125 W/m^2·K for the DHWT, whereas the

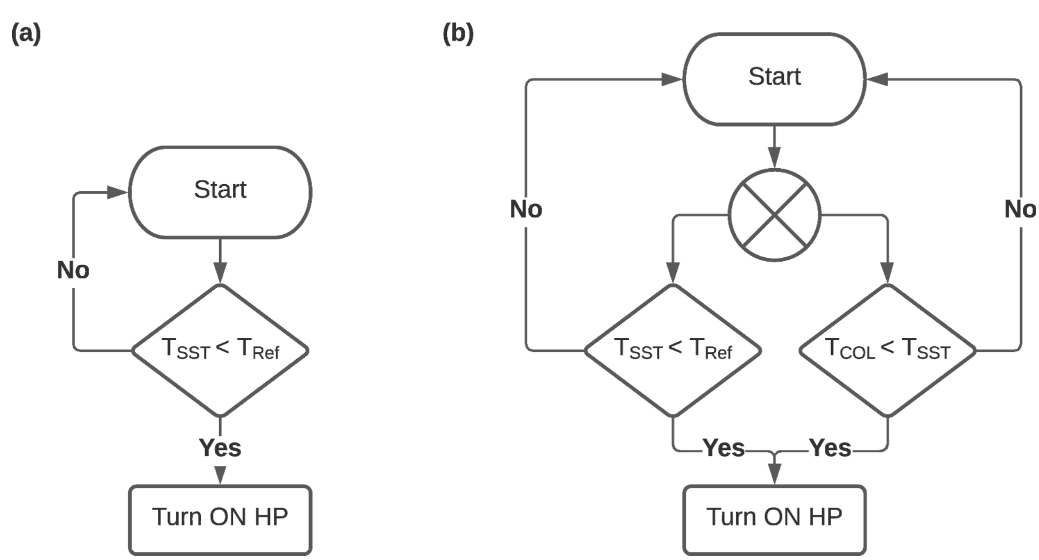

Fig. 2. The control strategies for the heat pump where (a) Control A, and (b) Control B.

SST heat loss coefficient is a function of the selected construction materials; counterflow heat exchangers (Type 5b) with overall heat transfer coefficient of 3.931 kW/m^2·K; and auxiliary heaters (Type 6) with an efficiency of 93%. The secondary units are: single speed centrifugal pumps (Type 3b), inlet and outlet pipe ducts (Type 709), three-way valves (Type 11 h), controlled flow diverters (Type 11f), tempering valves (Type 11b), soil temperature profile for the SST (Type 77), weather data (Type 15-3), time-dependent forcing functions for the heating and DHW demand profiles (Type 9c), and controllers (Type 2b).

The thermal performance of a fluid-filled sensible energy storage tanks (Type 4c), subject to thermal stratification, can be modeled by assuming that the tank consists of N (N <= 100) fully mixed equal volume segments. The degree of stratification is determined by the value of N. If N is equal to 1, the storage tank is modeled as a fully mixed tank, and no stratification effects are possible. At the current work, the storages are divided into 12 nodes for considering the stratification effect. This instance of Type 4 models a stratified tank having variable inlet positions such that entering fluid may be added to the tank at a temperature as nearly equal to its own temperature as possible. This instance further assumes that losses from each tank node are equal and does not compute losses to the gas flue of the auxiliary heater.

2.4. Thermal performance

The final demand for imported offsite energy can be examined for the evaluation of the solar community performance. Several specific metrics may, therefore, also be useful to compare case studies. The coefficient of performance (*COP*) is introduced to assess the heat pump seasonal performance. Besides, the solar fraction (*SF*) is a common indicator that describes the fraction of energy demand met by solar energy. Thus, the *SF* is calculated directly through determining the total energy consumption due to using the auxiliary heaters for heating and DHW purposes.

$$\boldsymbol{COP} = \frac{\sum_{i=1}^{n} \dot{Q}_{HP_i}}{\sum_{i=1}^{n} \dot{Q}_{consumption_i}} \tag{1}$$

$$\boldsymbol{SF_{SH}} = 1 - \frac{\sum_{i=1}^{n} \dot{Q}_{Aux1_i}}{\sum_{i=1}^{n} \dot{Q}_{Heating\ load_i}} \tag{2}$$

$$SF_{DHW} = 1 - \frac{\sum_{i=1}^{n} \dot{Q}_{Aux2_i}}{\sum_{i=1}^{n} \dot{Q}_{DWH\ load_i}} \tag{3}$$

where $\dot{Q}_{HP}$ and $\dot{Q}_{consumption}$ are the energy supplied and consumed by the heat pump. While $\dot{Q}_{Aux1}$ and $\dot{Q}_{Aux2}$ are the duty of auxiliary heater (MW) during a year of operation for n hours, whereas $\dot{Q}_{Heating\ load}$ and $\dot{Q}_{DHW\ load}$ are the total heating energy and DHW used in the buildings.

Another key factor of the SDHS is the efficiency of the SST which can be defined as one minus the ratio of annual energy losses throughout the SST over the heat transfer rate through the heat exchanger HE_1.

$$\boldsymbol{\eta_{SST}} = 1 - \frac{\sum_{i=1}^{n} \dot{Q}_{SST\ loss_i}}{\sum_{i=1}^{n} \dot{Q}_{HE_{1_i}}} \tag{4}$$

This effectiveness relies on another SST thermal classification which is the thermal energy losses in the SST, and it can be measured based on the thermal losses across the upper, lateral, and lower storage sides. The heat loss in these areas relies on the building material, the construction component, the ground conditions and the height-to-diameter ratio. While h_{conv} which is the convective heat transfer coefficient between the SST and the environment is considered 10 W/m^2·K. Moreover, λ_G which is the ground thermal conductivity is considered 3 W/m·K.

2.5. Economic indicator

The 40-year life cycle cost (LCC) of the SDHS in its net present value format is utilized as an economic indicator [38]. The LCC incorporates the initial cost (IC), operational cost (OC), maintenance cost (MC), and replacement cost (RC), as expressed in Eq. (5) [36,37].

$$NPC = IC + OC + MC + RC \tag{5}$$

The overall initial cost of investment consists of several items such as the cost of the equipment purchase, installation, and transportation, including the cost of any contingencies and it can be expressed as follows [37]:

$$IC = (1 + \alpha_{CF}) \sum_{k} (PEC_k.FBM_k) \tag{6}$$

Where PEC_k represents the purchase cost of equipment unit k, while the bare module factor FBM_k is responsible for the installation and transportation expense of unit k. α_{CF} denotes the contingency factor. The cost component PEC_k can be updated from the initial value in the base year A to the year of installation B based on the Chemical Engineering Plant Cost Index (CEPCI) using the following equation:

$$PEC_k = PEC_k^{yearA} \frac{CEPCI^{yearB}}{CEPCI^{yearA}} \quad \forall k \tag{7}$$

The initial cost of purchasing unit k in year A (PEC_k^{yearA}) can be estimated for various equipment units using Eqs. (8) to (12).

$$PEC_k^{yearA} = \alpha_k CAP_k^{\beta_k} \quad \forall k = COL,\ DHW,\ AUX \tag{8}$$

$$PEC_k^{yearA} = \alpha_k \left(CAP_k^{\beta_k} \right) CAP_k \quad \forall k = HP \tag{9}$$

$$PEC_k^{yearA} = CAP_k^{\beta_k}.10^{\left[\alpha_k (log_{10} CAP_k)^{\beta_k}\right]} \quad \forall k = HE_1,\ HE_2,\ HE_3 \tag{10}$$

$$PEC_k^{yearA} = \alpha_k \ln\left(\frac{CAP_k}{1000}\right) + \beta_k \quad \forall k = P_1, P_2, P_3, P_4 \tag{11}$$

$$PEC_k^{yearA} = Ins_{SST} + Con_{SST} \quad \forall k = SST \tag{12}$$

Where:

$$Ins_{SST} = \alpha_k CAP_k^{\beta_k} \quad \forall k = XPS,\ MW,\ FG \tag{12.1}$$

$$Con_{SST} = \alpha_k CAP_k^{\beta_k} \quad \forall k = NC,\ HPC \tag{12.2}$$

$$Con_{SST} = \alpha_k e^{\left(\frac{\beta_k}{10^5} CAP_k\right)} \quad \forall k = UHPC \tag{12.3}$$

Here α_k and β_k are the equipment cost parameters, CAP_k is responsible for the design variables of equipment unit k. The design variables are the area of the solar collector (A_{COL}), the volume of the fully stratified storage tanks (V_{SST}, V_{DHWT}), types of insulation materials used for the SST (*XPS*, *MW*, *FG*) which includes extruded polystyrene, mineral wool, and foam glass gravel, respectively, types of the SST construction material (*NC*, *HPC*, *UHPC*) comprising of normal concrete, high-performance concrete, and ultra-high performance concrete, respectively, area of heat transfer for the heat exchangers (A_{HE1}, A_{HE2}, A_{HE3}), and the mass flow rates of discharge for the pumps ($\dot{m}_1$, $\dot{m}_2$, $\dot{m}_3$, $\dot{m}_4$). The total operating cost (C_o) is the discounted summation of all annual operating costs and can be expressed as follows:

$$OC = C_M PWF_M + C_P PWF_P + C_{AUX} PWF_{AUX} \tag{13}$$

Where the C_M indicate the annual maintenance, C_P is the electricity cost due to the recirculation pumps, and heat pump. While C_{AUX} is the energy cost of the auxiliary heaters (natural gas boilers). The term *PWF* reflects the present worth factor which is calculated for the specific cost of

Table 1
Decision variables for SHDS defined by circuit name.

Circuit name	Decision variable	Unit	Uniform	Ref.
Supply field circuit	Solar field area (A_{COL})	m^2/MWh/a	0.1:2	[9,41]
	Solar field inclination angle (β_{COL})	o	20:70	[26]
	No. collector in series (N_{COL})	-	1:5	
	HP fraction capacity (FC_{HP})	%	10:100	
	HP turn on ref. temperature (T_{ref})	^{o}C	40:60	
SH distribution circuit	Seasonal storage volume (V_{SST})	m^3/MWh/a	1:20	[11,42]
	Height to width SST ratio (HDR)	m/m	0.3:1.5	[43,44]
	AUX_1 fraction capacity (FC_{AUX1})	%	10:100	
DHW distribution circuit	DHWT volume (V_{DHWT})	m^3/MWh/a	0.05:0.25	[9,45]
	Height to width DHWT ratio (HDR_{DHWT})	m/m	1:2	[46,47]
	AUX_2 fraction capacity (FC_{AUX2})	%	10:100	

operation taking into account the inflation rate (*i*) and the rate of interest (*r*) over the lifetime of the proposed system as expressed in Eq. 13:

$$PWF = \begin{cases} \frac{1}{d-i}\left[1-\left(\frac{1+i}{1-d}\right)^{N_e}\right] \forall i \neq d \\ \frac{N_e}{1+i} \forall i = d \end{cases} \tag{14}$$

The cost of replacing several equipment units of the proposed SDHS can be estimated as shown below:

$$\text{RC} = PVF_n \sum_k (PEC_k . FBM_k) \tag{15}$$

Here PVF_n is the present value factor of the future cash flows in the year *n*. The equipments which will incur a replacement cost in our study due to a high rate of depreciation over the system's lifespan are the solar collectors, storage tank used for DHW, heat pump, heat exchangers, and auxiliary heaters.

Moreover, it is possible to establish SDHS economic feasibility dependent on the payback period [39]. It is commonly used for lifetime evaluation of energy system output and is typically expressed in years. The smaller the payback period, the better a project is expected to be. By dividing the future system value (NPC) by the annual cost savings for utilizing the SDHS instead of natural gas boiler, the calculation of the payback period can then be performed:

$$Payback\ period\ (PB) = \frac{NPC}{Annual\ cost\ saving} \tag{16}$$

2.6. Optimization problem

The optimization process is aimed to minimize both the usage for auxiliary heater share $\left(AUX_{share} = \frac{\sum_{i=1}^{n} \dot{Q}_{Aux_i}}{\sum_{i=1}^{n} Q_{Heating\ load} + \sum_{i=1}^{n} Q_{DHW\ load}}\right)$ and LCC. The problem is defined as:

$$\begin{aligned} & min\{f_1(x), f_2(x)\} \\ & s.t.\ \ h(x) = 0 \\ & \qquad g(x) \geq 0 \\ & lb_i \leq x_i \leq ub_i \quad \boldsymbol{i} \in \{1, \cdots, 11\} \end{aligned} \tag{17}$$

Where f_1 is the share of auxiliary heating and f_2 is the life cycle cost, while *h* represents the equality constraints solved implicitly in TRNSYS. The symbol *g* represents the inequality constraints, which reflects certain technical constraints comprising an annual solar collector field efficiency of 60%, SST efficiency above 50%, and global solar fraction of 50%, as mentioned by Bauer et al. [11] and Solites [40]. While lb_i and ub_i are the lower and upper bounds for all decision variables. Table 1 shows the decision parameters.

Following the methodology regards coupling the TRNSYS simulation with MATLAB for developing a multi-objective optimization problem mentioned by Abokersh et al., [28]. Two heat pump control strategies are utilized where a separate optimization was performed for each control strategy. Optimization was performed with the MATLAB, through using a genetic algorithm where The optimization uses the NSGA-II algorithm with 1000 initial population due for 300 generations., and the Pareto fraction was 0.6 based on Alajmi et al.[48]. Additional calculations during the optimization process were performed with MATLAB [28,35].

3. Case study

The proposed SDHS is designed to satisfy the heating requirement for a limited population comprises of 10 buildings located in Madrid (Spain). Every building has 28 apartments with 90 m^2 of the appropriate area [49] per apartment. It is fitted with a radiant heating system and hot water tap to accommodate a 50°C and 60°C requirements for SH and DHW following Tulus et al.[9]. The total heating requirement for each building is 191.34 MWh /year. The developed SDHS is validated based on Tulus et al.[9] and Abokersh et al.[28].

3.1. Economic inputs

Following Tulus et al. [37], the maintenance cost of the SDHS is estimated to be 1.5% of the initial investment cost. Furthermore, according to the United Nations Environment Programme, the lifetime of the SDHS is 40 years [38], where several equipment including the solar collectors, heat exchanger DHWT and auxiliary heaters need to be replaced after only 20 years of operation. Based on the EUROSTAT database [50], the prices of natural gas and electricity are estimated to be 0.0526 and 0.1873 Euro/kWh, respectively. Moreover, the inflation rate associated with natural gas and electricity is 5.9% and 5%, respectively [9]. According to Braungardt et al. [51], the inflation rate associated with the proposed system throughout its lifetime is set to be 2.3%, with a discount rate of 3.5%. Furthermore, the initial cost parameters are outlined in Table 2.

3.2. Optimization scenarios

Generally, five scenarios display optimization outcomes where:

- **Scenario 1**: It represents the minimum cost solution with zero limits on possible usage for natural gas (Min. cost).
- **Scenario 2** to **4**: The natural gas limit of 25%, 50%, and 75% which is allowed in scenario 2 up to 4 would rely on reducing the natural gas usage by 25%, 50% and 75%, respectively against scenario 1.

Table 2
The economic parameters for the initial cost of the heat pump integrated into SDHS.

Unit	Options	α_k	β_k	CAP_k	Range	Base year	Ref.	FBM_k
Solar collector		974.2	0.8330	Aperture area (m^2)	4000-15,000	2007	[52]	1.00
Heat pump		2053.8	-0.348	Thermal power (kW)	600-100,000	2014	[53]	1.00
DHWT		3955	0.6500	Volume (m^3)	1-100,000	2007	[54]	1.00
Auxiliary heater		225.0	0.7460	Duty (kW)	600-10,000	2001	[37]	2.10
Heat exchanger		3.133	0.3310	Exchange area (m^2)	10-1000 m^2	2001	[37]	3.29
Pump (P_1, P_2)		389.0	283.2	Mass flow rate (kg/h)	15000-100,000	2009	[55]	3.24
Pump (P_3, P_4)		389.0	717.0	Mass flow rate (kg/h)	15000-100,000	2009	[55]	3.24
SST insulation	*XPS*	561.09	0.397	Material thickness (m)	0.05-0.8	2017	[56]	1.00
	MW	1902.7	0.942	Material thickness (m)	0.05-0.8	2018	[57]	1.00
	FG	311.41	0.968	Material thickness (m)	0.05-0.8	2014	[58]	1.00
STT construction	*NC*	4178.1	-0.394	Volume (m^3)	1-100,000	2000	[59]	1.00
	HPC	2575	-0.363	Volume (m^3)	1-100,000	2004		1.00
	UHPC	90.83	-3	Volume (m^3)	1-100,000	2004		1.00

- **Scenario 5**: The SDHS model causes minimum usage for the natural gas (Min. GAS) which in other words represents the solution with the highest share for solar energy.

4. Result and discussion

This stage involves the testing of the capability of the different HP control strategies in enhancing the techno-economic feasibility of SDHS via the Madrid case study in a small-sized community of 10 buildings where the design variables of different equipment are taken into account while formulating the optimization problem.

Fig. 4 indicates optimum system costs under different conditions in *NPC* term and payback period. A clear tradeoff between the proposed objective functions is indicated since the movement from scenario 1 to 5 at both controls (A), and (B) settings increase the total cost while. Under the control (A) setting, the NPC at scenario 1 (Min. cost) solution is 72.2 Euro/MWh. At the same time, it is increasing up to 144.7 Euro/MWh in scenario 5 (Min. Gas) solution. Using the latter value, the payback period for scenarios 1 to 5 increased from 31 to 63 years. In comparison, optimum strategies in Pareto at smaller communities (10 buildings) do not deliver a significant economic gain because only Scenario 1 decreases the cost and payback below the 40 years which is the life cycle of SDHS.

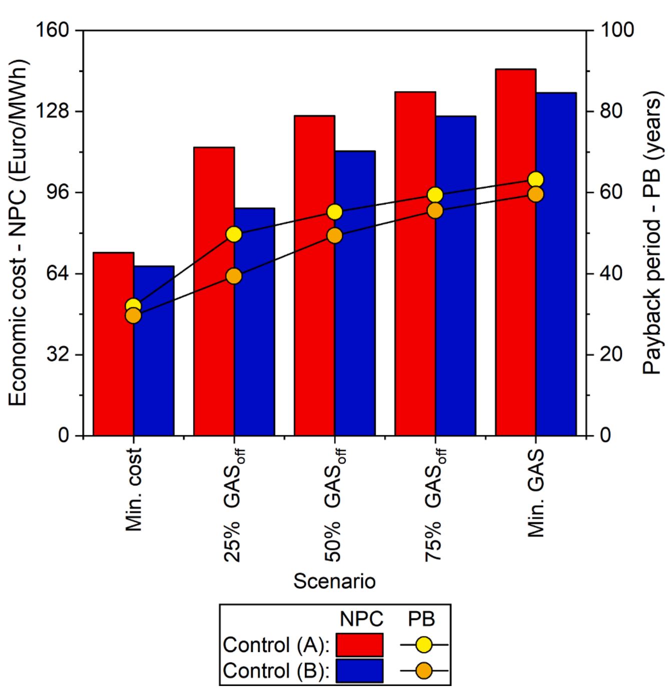

Fig. 4. The economic benefits and the payback period for the optimal Pareto solutions of the HP integrated with SDHS under control strategy (A) and (B).

On the other hand, The Min. cost solution under control (B) improves the NPC by 7%. In contrast, moving from scenario 2 to 5 keeps this improvement, and it is reflected in the payback period, which is moved from 29 years to 59 years. This high payback period is due to the low natural gas prices, which reduces the operational cost of the natural gas boiler and subsequently increase its competitivity in comparison to SHDS.

Besides the economic benefits, the proposed methodology also calculates the optimal operating patterns of each technology. Thus, the percentage shares of grid electricity, fossil fuels (natural gas) and solar energy, as shown in Fig. 5. Under control (A), the solar energy represents around 75% of the total energy share, whereas the natural gas and electricity from the grid share 15% and 10% respectively. With the movement from scenario 2 to 5, the natural gas share and electricity reduce where the natural gas share reduces from 8% in scenario 2 to 0.3% in scenario 5. For the share of electricity consumed by HP, it reduces from 8% to 2%. The increment covers this reduction by the usage of solar energy which its share increases up to 98% in scenario 5.

On the other hand, Control (B) always keeps the share of the solar energy higher where it increases from 82% at scenario 82% to 99% in scenario 5. This increment is associate with the reduction in the natural gas and electricity consumed by the HP where the natural gas usages reduce from 17% at scenario 1 to only 0.12% in scenario 5. Besides, using control (B) reduces the usage dramatically for HP since under this control, the HP is utilized only to cover the shortage in SST during the high demand period of the season.

Following the optimal solutions under control (A) and (B), For the optimum characteristics and specifications of the Pareto solutions defined by a circuit in various situations as seen in Table 3, the suggested approach provides a comprehensive overview. The table typically displays the most frequently selected control system decision variables in different conditions for the gas mitigation. In the supply circuit, most of the optimal Pareto solutions at both control strategy remains the A_{COL} between 0.36 and 1.14 m^2/MWh/a. In contrast, the inclination angle stays in a narrow range between 42:50°. In comparison, for all cases, the amount of linked solar collectors in series is always at 5. Just about 0.12:0.21 m^3/MWh /a for most optimal strategies is utilized in the DHWT system, as the DHWT is mostly used for everyday uses, without long-lasting storage, while the HDR_{DHWT} divergence range is about 1.2:1.9. The optimum properties of the SST configuration in different community sizes on the SH circuit reveal that the V_{SST} range from 1.8:13.5 m^3/MWh/a whereas 0.47:0.71 for HDR for both situations for gas reduction situations.

Regarding the capacity of the auxiliary heater, the FC_{AUX1} is varying between 10.3:11.6 %. At the same time, the FC_{AUX2} is varying between

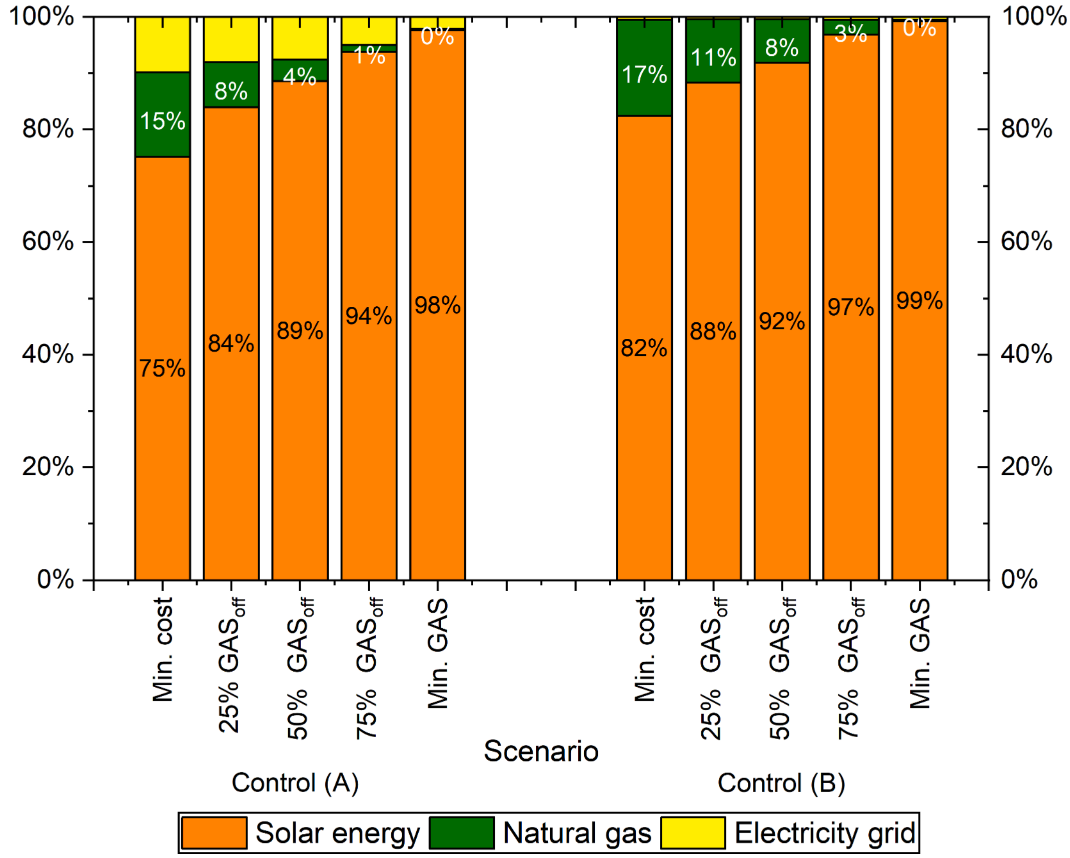

Fig. 5. The share of technologies for the optimal Pareto solutions of the HP integrated with SDHS under control strategy (A) and (B).

Table 3
Pareto optimal solutions of the HP integrated with SDHS layout to fulfill the demand of 10 Madrid buildings at HP control strategy (A) and (B).

Circuit name	Decision variable	Unit	Control (A)	Control (B)
Supply field circuit	A_{COL}	m^2/MWh/a	0.36:1.14	0.41:1.11
	β_{COL}	o	45:50	42.9:50.1
	N_{COL}	-	5	5
	FC_{HP}	%	48.2:69.1	13.5:19.1
	T_{ref}	^oC	50.2:58.9	54.2:56.8
SH distribution circuit	V_{SST}	m^3/MWh/a	2.01:13.5	1.87:12.4
	HDR	m/m	0.47:0.76	0.47:0.71
	FC_{AUX1}	%	10.3:11.6	10.8:11.3
DHW distribution circuit	V_{DHWT}	m^3/MWh/a	0.12:0.22	0.14:0.21
	HDR_{DHWT}	m/m	1.23:1.88	1.3:1.93
	FC_{AUX2}	%	17.2:34.8	19.1:54.6

17.2:54.6 %. These configurations of the SDHS circuits will be reflected in the *NPC* breakdown under both control strategies.

As shown in Fig. 6, the investment cost in the control strategy (A) is around 2.5 Million Euros for scenario 1, and it increases to 6.5 Million Euros at the scenario 5 (Min. GAS). While in term of the operational cost, it's around 2.25 Million Euros, whereas between scenario 2 and 5 it's almost the same where it's around 2.75 Million Euros. With the increment in the share of solar contribution, the replacement cost increases from 0.65 Million Euro up to 1.2 Million Euro. In control strategy (B), the reduction in the *NPC* shown in Fig. 6 is reflected in its breakdown where the investment cost reduces only by 2.8% at scenario 1, and it is extended up to 5.7% in scenario 5. In terms of the operational and replacement costs, the reduction is up to 18.7%.

As illustrated in Fig. 7, the suggested SDHS thermal output is assessed using a mixture of minimal output indicators; these indicators include SST efficiency and their relative solar fractions as well as the heat pump *COP*. Under both control strategy (A and B), a small variation in the SF_{DHW} is can be seen with a shift in situations or the control, where the lowest SF_{DHW} is revealed in scenario 1 owing to the limited usage of solar collector, and it is around 97%. Regarding the SST performance, under both control strategies (A and B), the η_{SST} remains around 88% for all scenarios. The SF_{SH} slowly raises from 75% in Scenario 1 (minimum cost) to 98% in Scenario 5 (minimum gas), with the Solar Fraction under Control strategy (A), with increasing gas constraints (rise in the use of renewable energy instrumentation). Under the control strategy (B), the solar fraction is in the two extreme ranges of optimum situations (minimum cost and minimum GAS optimum strategies) is improved by 13.3% and 2% in scenario 1 and 5, respectively. This is due to the higher share of solar energy compared to the control strategy (A). Finally, in terms of the *COP*, the Control strategy (B) extremely improve the HP performance especially in the scenario 1 and 2 where the *COP* is above 6 for both scenarios, whereas it is only around 5.5 for all scenario under control strategy (A).

In Fig. 8, the simulated yearly overview of the thermal energy in a monthly resolution under the control settings (A) and (B) for the min. cost optimal solution is presented. While the energy supplied by the SDHS to the consumers is represented as a positive input. In contrast, the energy stored in the SST from February to September is shown as a negative input. The stored heat is gradually used during the autumn season and the first half of the winter. For the whole winter season, the energy supplied by the SDHS plant to cover the heating needs mainly to come from a combination of the solar collectors, SST, DHWT and heat pump. In the event of extreme requirements, the auxiliary heaters are operated to provide the heat if the proposed SDHS is unable to do so on its own.

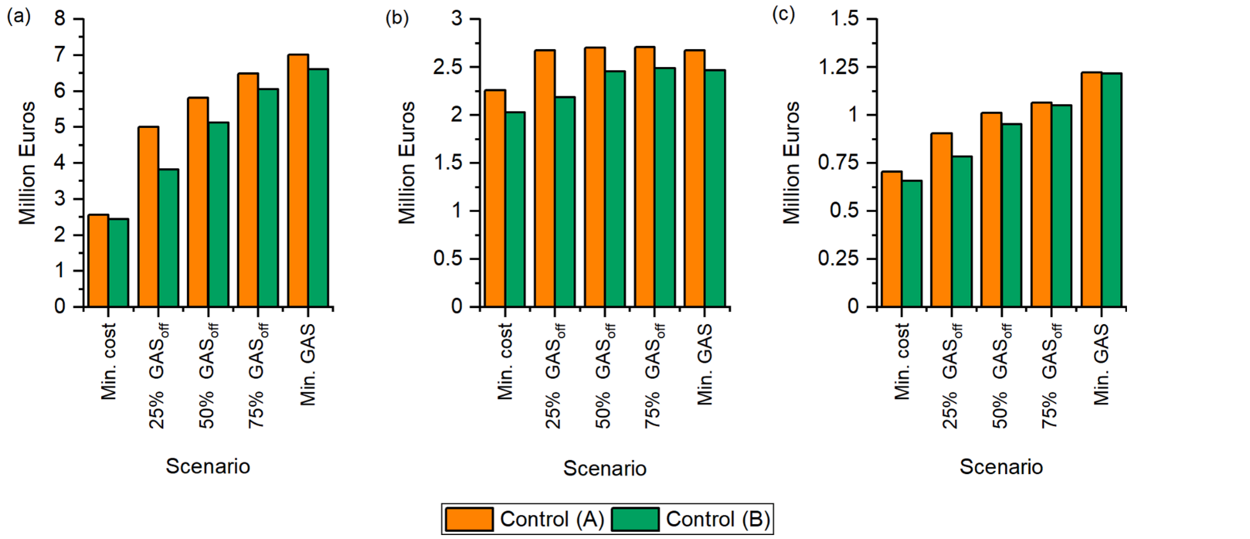

Fig. 6. Breakdown of the ***NPC*** including the shares of; (a) initial capital cost, (b) operational cost, and (c) replacement cost for Pareto optimal solutions under HP control strategy (A) and (B) at the 5 optimal scenarios.

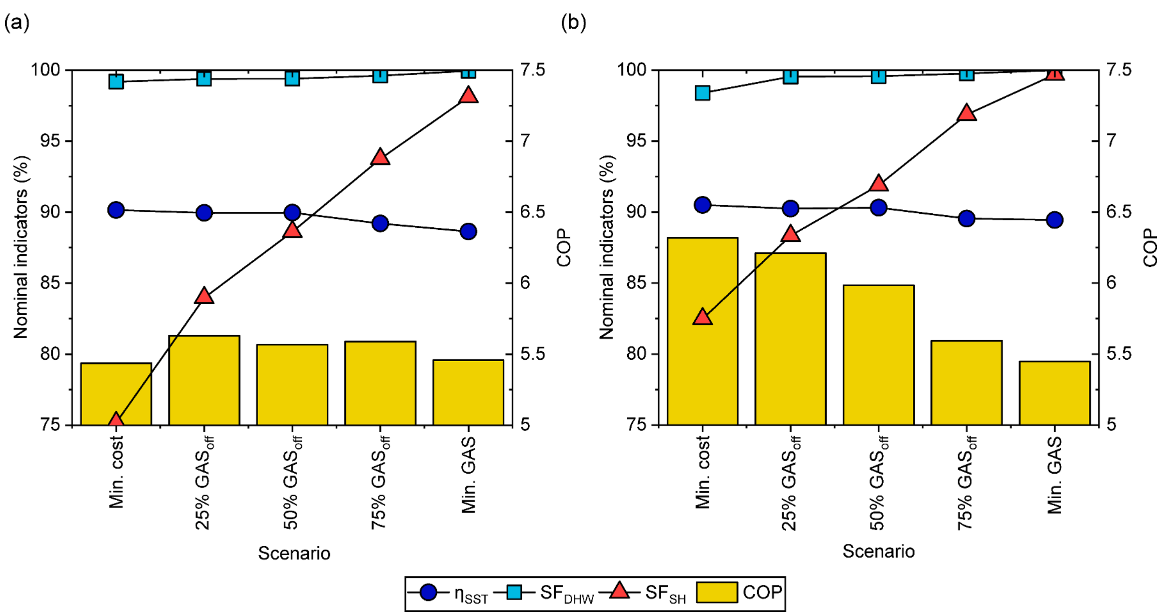

Fig. 7. Thermal performance indicators for the optimal Pareto SDHS solutions, where (a) SDHS under HP control strategy (A), and (b) SDHS under HP control strategy (B).

It is interesting to notice that the profile of solar radiation incident on the solar thermal collectors and the energy stored in seasonal storage is less under the control setting (B) as compared to (A). Also, the solar collector provides energy for a longer duration when control (B) is applied because much of the accumulated energy in the SST is already drained during the early winter months. This is coherent with the fact that the minimum cost solution under (B) uses a smaller collector area with maximum efficiency. Simultaneously, since the improvement of cost efficiency for the SST is given a priority, this penalizes the energy performance of the storage. The amount of energy supplied by the heat pump under setting (B) is minimal compared to (A). This is related to the fact that the control strategy (B) for the HP relies on both collector and storage operation and, therefore, the usage of the heat pump is minimal. In one hand, this leads to an improved seasonal performance factor for the heat pump. On the other hand, control (B) also significantly lowers the heat pump capacity. Moreover, the use of the auxiliary heater is also marginally reduced in (B). This sums up that by using the heat pump control B is able to help the seasonal storage and the solar collector to reach temperature stabilization in the proposed SDHS. The design and control optimization have created a balance among the various sources of heat, i.e. the solar collector, storage tanks, heat pump and auxiliary heater without failing to supply the SH and DHW requirements of a community of 10 residential buildings located in Madrid, Spain.

Following the overview for the thermal energy in a monthly resolution, Fig. 9 shows the temperature profile for the SST under control (A& B) at Min. cost optimal solution. The usage of the heat pump assists in solving the overheating problem in the SST during the summer period where the SST stays around 88°C control strategy (A). Furthermore, this value enhanced more with using control (B), where the maximum monthly average temperature inside the SST is around 85°C. During the winter period, with the higher contribution for the heat pump to the heat load under control (A) as shown in Fig. 8, the heat pump assists in reducing the temperature inside the SST in comparison to control (B). During December and January, the SST temperature stays around 43°C

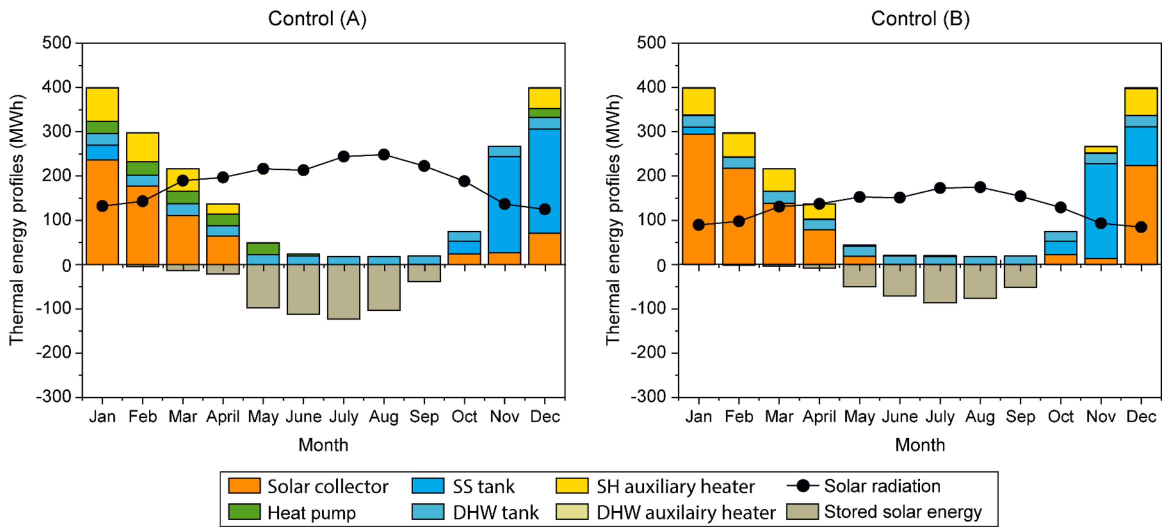

Fig. 8. Annual thermal energy profiles of Min cost Pareto optimal solution for the HP integrated into SDHS at two control strategies (A) and (B) which covers SH and DHW demand of to cover the demand of 10 buildings located in Madrid.

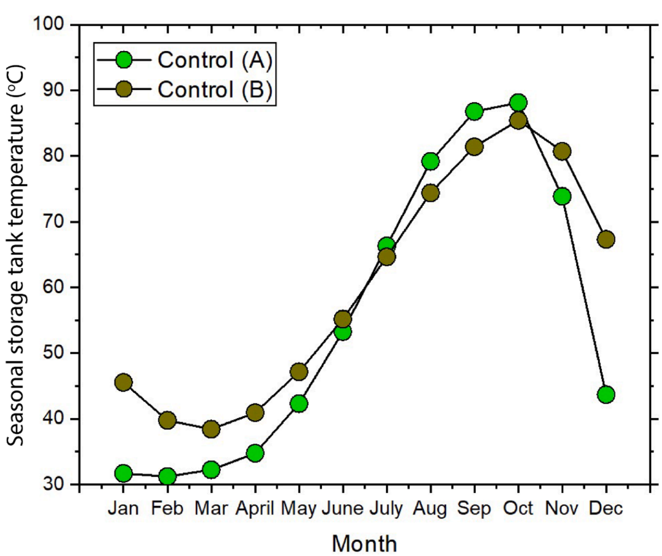

Fig. 9. SST monthly temperature profile under control strategy (A &B) for the heat pump.

and 31°C for control (A). While it increases to 45°C and 67.3°C under control (B) due to the higher SST storage capacity due to its volume.

As shown in Fig. 9 during the summer period, the control (A) reaches a higher temperature in the SST than in control B, although it starts from a lower temperature. This is due to the heat pump control and the seasonal storage tank volume. In control (A), the seasonal storage tank has a smaller volume that's why is a higher temperature during summer is indicated. While during the winter period, the small tank size makes that stored heat depleted fast during the high demand in December and the temperature in the seasonal storage so low from January. At the same time, the heat pump works in extensive rate during the remain of the winter period. In the other hand, the combination of control(B) for the heat pump and the higher volume of the seasonal storage tank keeps the temperature at a higher level during winter and lower during summer

5. Comparison of the proposed HP+SDHS model to other projects

Since such solar community does not exist in Spain, this section compares the proposed simulation optimal solutions against other real SDHS projects. This section compares the proposed simulation optimal solutions against simulation study for Spain and a real project located in Germany based on nominal performance indicators. These simulations include Guadalfajara et al.[60]. While the München plant was developed as a part of the "Solarthermie2000plus" project [12]. The Min. cost-optimal solution at a community size of 10 buildings under control strategies (B) for the HP is selected for comparison purposes. The assessment compares the heating demand, the solar collector area, the seasonal storage volume, and the solar fraction, as shown in Table 4.

The renewable energy fraction has a favorable performance compared to the simulated Spanish plant and German plants, where a solar fraction of 82.1% is indicated for the low-performance solution (Min. cost-optimal solution). While the Spanish plants could not exceed a solar fraction of 54%, this vast difference between the Spanish project and the present study can partly attribute to the difference in the solar collector area to the heating demand ratio. Furthermore, it is found that the project located in München is reasonably comparable with our simulation case study with some differences due to the climate conditions, and it has a lower solar fraction of only 47%.

6. Conclusion

In this study, a dynamic model for a central heat pump coupled with a solar district heating system (SDHS) located in Madrid is developed. The proposed simulations are connected with an optimization method to evaluate the advantages of enhanced techno-economic efficiency of the suggested framework under two control strategies for the HP. The preceding concludes the study for the problem output formulated for optimization under control strategy (A) and (B):

Table 4
Comparison of the HP+SDHS optimal design under control (B) for 10 buildings to real systems located in Zaragoza [60], München [61].

	Madrid (Our optimization)	Zaragoza Spain (2014)	München Germany (2007)
Heat demand (MWh/a)	1913.4	5488	1976
A_{COL} (m^2/MWh/a)	0.41	0.584	1.36
V_{SST} (m^3/MWh/a)	1.87	3.509	2.88
SF_{SH}	82.1%	54%	47%

- The determined optimum strategies display a steady rise in the technological and economic use of HP+SDHS where under control (A), NPC is increased from 72.2 Euro/MWh to 144.7 Euro/MWh. On the other hand, under control (B), the NPC is improved by around 7% in all scenarios where the NPC is reduced up to 67.12 Euro/MWh. This improved is reflected in the payback period where control (B) can reduce it up to 29 years, and it can be improved with changing the policies regarding the natural gas and movement toward renewable energy systems.
- In terms of the technical performance, usage of control (B) increase the solar energy share where it is around 85% at the Min. Cost solution, whereas the solar fraction for the same scenario is only around 75% for control (A). Furthermore, control (B) improves the COP, and it achieves around 6 in contrary to control (A) where it achieves only 5.5.

In summary, this study proposed the techno-economic advantage for different types of heat pump control strategies at a small community of 10 buildings. In general, the results confirm the significant effect for the HP control in the performance of the SHDS. This study can be a key for different stakeholders and bring the SDHS as a feasible solution in the market incorporates with changing the market policies regarding the natural gas prices.

CRediT authorship contribution statement

Mohamed Hany Abokersh: Conceptualization, Methodology, Formal analysis, Software, Data curation, Visualization, Writing – original draft. **Manel Vallès:** Conceptualization, Writing – review & editing, Supervision. **Kangkana Saikia:** Investigation, Writing – original draft. **Luisa F. Cabeza:** Funding acquisition, Writing – review & editing. **Dieter Boer:** Resources, Supervision, Writing – review & editing, Project administration.

Declaration of Competing Interest

Potential conflict of interest exists: Bottom of Form We wish to draw the attention of the Editor to the following facts, which may be considered as potential conflicts of interest, and to significant financial contributions to this work: The nature of potential conflict of interest is described below: No conflict of interest exists. We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

Acknowledgments

The work is funded by the Spanish government RTI2018-093849-B-C31 and RTI2018-093849-B-C33. The authors would like to thank the Catalan Government for the quality accreditation given to their research group (GREiA - 2017 SGR 1537, AGACAPE - 2017 SGR 1409). GREiA is a certified agent TECNIO in the category of technology developers from the Government of Catalonia. This work is partially supported by ICREA under the ICREA Academia programme. This work is partially funded by the Ministerio de Ciencia, Innovación y Universidades – Agencia Estatal de Investigación (AEI) (RED2018-102431-T). This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 713679 and from the Universitat Rovira i Virgili (URV).

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